The Optimal Allocation of Ocean Space: Aquaculture and Wild-Harvest Fisheries

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In many estuarine and ocean areas, aquaculture is seen as an alternative to traditional commercial fish harvesting practices. A significant problem hindering the emergence or the continuing growth of aquaculture in many areas is the conflict that arises among it and other competing ocean uses. Real world examples include the incipient conflict between rights-based commercial fisheries and the marine culture of the green-lipped mussel (*Perna canaliculus*) in New Zealand and the debate over shellfish leases and wild-harvest production of hard clams (*Mercenaria mercenaria*) in small estuaries on Cape Cod. We consider the resource manager's problem of allocating ocean space in a circumscribed region defined by a fishery. We develop a bioeconomic framework to help clarify the choice of the optimal scale of aquaculture when that use impacts the fishery. We identify a range of potential impacts, both positive and negative, but we focus on negative impacts that affect the carrying capacity of the fish stock. Numerical simulations are developed to illustrate two cases: (1) aquaculture and fishery uses compete only over ocean space; and (2) these uses compete both over ocean space and in the downstream product market. Preliminary simulation results for a hypothetical case focusing on fluke (*Paralicthys dentatus*) in Rhode Island Sound suggest that social optima often may be associated with corner solutions (*i.e.*, the ocean area should be devoted exclusively either to aquaculture or to the fishery). These results imply that, under certain conditions, the coexistence of both types of uses may not be economically optimal.

Key words: aquaculture, wild-harvest fishery, bioeconomics, spatial allocation, carrying capacity, user conflicts

1. INTRODUCTION

In this paper, we examine the interactions between marine (or estuarine) aquaculture and a wild harvest fishery. These two uses of the ocean may vie over physical space, impose external costs (or benefits) on each other, and compete in downstream markets. In many instances, fishermen and aquaculturists may gain access to the ocean under different sets of rules and legal rights. Where such disparate property systems are not fully integrated, and uses are partially or fully exclusive, conflicts are bound to arise. If property rights are ill defined, or if they are spread across a large number of users, then classic coasean solutions to external effects may not be realizable.

Here, we explore the implications for the coexistence of both commercial fisheries and aquaculture in a particular ocean region. We consider first what happens when aquaculture is introduced into a region where an open-access fishery is established. Next, we consider the effects of aquaculture on the price of quota in a fishery in which a system of individually transferable quotas (ITQs) has been implemented. Finally, we develop a model to determine the optimal long-run, steady state scales of fishing and aquaculture, assuming that the fishery can be regulated with taxes or ITQs. We develop a numerical example to illustrate the sensitivity of the optimal outcome to alternative parameter values.

1.1. Potential Fishery-Aquaculture Interactions

A wide range of potential interactions may arise between aquaculture and commercial fisheries (Table 1). The type of interaction may depend upon the classes of species grown or caught and the technologies utilized for each activity. Interactions may involve the decrease (or increase) in the carrying capacity of wild stocks; possible increases in the costs of either wild harvest or aquaculture as more space is devoted to the alternative use; the culling of juvenile fish from a wild stock for growout in a culture facility; and the risks of genetic mixing or displacement and the spread of disease. These are the types of interactions that have been highlighted, mostly in a negative sense, by environmental groups (*cf.*, Goldburg *et al.* 2001). Although the culturing of one species could affect the status of a range of species or the characteristics of an entire ecosystem, in this paper, we focus mainly on the effects on a single species.

Table 1: Some possible marine aquaculture and wild fishery interactions. Key: K = the carrying capacity of the commercial fish stock is impacted (negatively or positively); C_f = the cost of fishing increases as the area allocated to aquaculture increases; C_a = the cost of aquaculture increases with increasing fishing effort; J = juvenile fish may be culled from the wild stock for growout; p(G) = the risk of genetic pollution; p(D) = the risk of the spread of disease.

	Wild Stocks ➡			
Aquaculture ⬇	Salmonids	Groundfish	Pelagics	Shellfish
Salmonids	p(G), p(D)	K, C_f, C_a	C_f, C_a	
Groundfish		K, C_f, C_a, J, p(G) , p(D)	C_f, C_a	
Pelagics		K, C_f, C_a	J, p(D), C_f, C_a	
Shellfish		C_f, C_a	C_f, C_a	C_f, C_a, J, p(D)

As one example, consider the shaded cell in Table 1 that describes potential interactions between the wild harvest and the culture of groundfish. The summer flounder or fluke (*Paralichthes dentatus*) is one groundfish species that has been proposed for culture in New England. Fluke would most likely be either hatched or culled from the wild stock and grown out in netpens, much like the growout of salmonids. The widespread allocation of areas in an estuary or coastal ocean to fluke culturing could impact the carrying capacity of the environment for the stock. The sign and size of the impact, however, is the subject of speculation and debate. Even if the nutrients supplied by the feeding of fluke in netpens acted to increase the actual carrying capacity for the stock, if the stock is not available for harvest because of the failure of fish to migrate out of the area allocated for culturing, then the "effective" carrying capacity for the commercial fluke fishery may be reduced. This issue is analogous to the question of the diffusion rate of a fish stock out of a marine reserve (Mullen 1989). As more space is allocated for aquaculture, there may be both a smaller stock available for fishing and more congestion in the areas remaining open for wild harvest. These effects could lead to increases in the cost of fishing. On the other hand, as more area is allocated for wild harvest, the cost of aquaculture might increase, if the potential for achieving economies of scale are constrained. Further, if the cultured fish are genetically different from the wild fish, then there is some potential for affecting the biological fitness of the wild stock if the cultured fish are released into the environment. Finally, the potential exists for the spread of disease from the cultured fish to the wild stock (or vice versa).

1.2. Literature and Cases

The potential for conflicts between commercial fisheries and aquaculture has been appreciated in only a few places to date, but it is likely to become a more significant problem as aquaculture continues to expand worldwide. At an FAO sponsored meeting in 1986 focusing on the problems of small-scale fisheries in the western Mediterranean, the participants identified "major problems in the competition between aquaculture and fisheries . . . over uses of space, living resources, human and financial resources, and market competition for seafood" (Charbonnier and Caddy 1986: 47).[1] In the early 1990s, in North West Connemara, on the west coast of Ireland, local fisherman perceived that the "expansion of [salmon] farms result[ed] in an increasing number of restricted areas for fishing" (Steins 1997: 3). The fishermen formed a shellfish cooperative to secure aquaculture licenses so that they could safeguard access to their historical fishing grounds. In New Zealand, Hickman (1996: 452) notes that the 30 year history of aquaculture there has been one of competition for coastal waters and that "on occasions direct competition has occurred between aquaculture and traditional fishery interests." Grey and Sullivan (2002) explain that commercial fishermen in New Zealand argue that ITQ rights include a guaranteed right to access ocean areas sufficient to catch the quota. There is now a two-year moratorium on all new marine farming in New Zealand ostensibly to develop a more rational approach to the allocation of ocean space (Grey 2002).

McVey (2001) of the US National Sea Grant College Program has argued that aquaculture and fisheries will need to be managed together in order to optimize value. In a similar vein, Ferlin (1986) calls for an integrated management approach to both improve marine fisheries and to develop the aquaculture industry.

The literature on the economics of aquaculture is small but growing rapidly. Existing studies in this area may be categorized into two groups. The first group focuses on the economics of aquaculture operations, including the

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[1] On the other hand, Jordana i de Simon (1998) reports that there has been no interference between fishing an aquaculture in the autonomous Community of Catalonia, Spain.

analyses of production processes (Kite-Powell *et al.* 2002a, 2002b; Kazmierczak and Caffey 1995; Arnason 1992; Karp *et al.* 1986) and downstream product markets (Engle and Kouka 1995; Kouka 1995).

The second group examines the biological and market interactions between aquaculture and commercial fisheries. For example, Anderson (1985a) models the interactions between ocean ranching (the hatching and release of smolts of anadromous fish, such as coho salmon (*Oncorhynchus kisutch*), which migrate into ocean waters and later return to be harvested by the rancher) and commercial fishing. The author shows that there is a range of prices within which both ranched and wild fish stocks can coexist. However, there is a limit price above which the wild stock could be driven to extinction through overfishing stimulated by the release of large numbers of the ranched fish. The range of prices under which both stocks can coexist can be increased either through restrictions on wild harvest fishing effort or by reducing the catchability of the ranched stock. Cooperative management can result in profits from both activities.

Anderson and Wilen (1986) examine the implications of private salmon ranching in the Pacific Northwest on market structure, salmon prices, wild harvests, ranch output, and salmon fishing regulation. The authors model the behavior of a dominant salmon rancher facing a competitive open-access fishery. Primary attention is given to the factors that influence the strategies of an optimally managed salmon ranch under selected institutional and biological constraints. The effect of such behavior is evaluated with regard to salmon prices, natural salmon stocks, ocean fishing effort, and ocean fishery productivity.

In another study, Anderson (1985b) presents a single-species model in which cultured finfish competes in the same market as a perfect substitute for a wild harvest product. There is no biological interaction or geographical competition between the aquaculture operations and the commercial fishery. The author concludes that the entry of competitive aquaculture firms leads to increases in the stock of wild harvest fish, thereby complementing wild harvest fishery management objectives, and benefits consumers through increases in the total supply of fish to the market and price reductions. Green and Kahn (1997) find a similar result and use it to argue for the subsidization of aquaculture.

1.3. Scenarios

We consider two general types of interactions: those over physical space and those in the market. We start with an examination of the competition between aquaculture and fishing over physical space in the ocean. Aquaculture may also compete with wild harvest fisheries solely in the market. This appears to be the situation in the world salmon market, where low cost aquaculture production may be causing the wild harvest fishery in Alaska to slump. Alaskan fishermen and processors have been attempting to differentiate the product, lately through an unsuccessful effort to certify the wild harvest as "organic." This type of competition is an interesting case in which technological innovation may lead to the displacement of more traditional forms of production, with potentially important ramifications for ecosystem health and social welfare. We do not consider this case explicitly in this paper, although the essence of the problem is found in a more general model that considers competition over physical space as well as in the downstream market.

2. COMPETITION OVER PHYSICAL SPACE

We begin with a traditional production function for a wild harvest fishery:

$$h_f = qXE \tag{1}$$

where h_f is the level of landings from the wild harvest stock, q is a catchability coefficient, X is the size of the natural fish stock, and E is a variable that represents aggregate fishing effort for a fleet of homogeneous vessels.

Let r be an intrinsic growth rate of the fish stock, and let K represent the fishery's carrying capacity in stock units. We assume that the fish stock is distributed uniformly over the area of the fishery, so that K can also be denominated in units of area.[2] Let S be the area devoted to aquaculture, and let K be a linear function of S so that the carrying capacity changes with S at a constant rate φ:

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[2] This assumption is critical to the analysis. If it is known that the stock is distributed nonuniformly, then it may be possible to site aquaculture operations in such a way as to reduce the likelihood of impacts on the fishery. Many jurisdictions use the historical distribution of fishing effort as a way to select locations for the siting of aquaculture facilities. This approach is not necessarily economically efficient, but it may minimize the costs associated with political conflicts.

$$K(S) = K - \varphi S \qquad (2)$$

In principle, K(S) could either increase or decrease with increases in S. An example of the former could occur where the nutrients from an aquaculture operation enhance local productivity. For example, lobster stocks are believed to benefit from the siting of mussel growout facilities. Examples of the latter include interference with the ecosystem to create conditions where fish cannot exist; the spread of disease from the cultured stock to wild fish; or even the release of genetically inferior stocks into the wild. In the following illustrations, we focus mainly on the case where $\varphi > 0$, implying that K(S) decreases as more ocean space is allocated to aquaculture.

We employ a simple surplus production model to describe the growth, F(X,S,E), of the wild stock when it is being fished:

$$F(X, S, E) \equiv \dot{X} = rX\left\{1 - \frac{X}{K(S)}\right\} - h_f(X, E) \qquad (3)$$

At a steady state equilibrium, equation (3) describes the classic downward sloping linear population equilibrium relationship between fishing effort E and the fish stock X. The intrinsic growth rate, r, is a fixed parameter. When $\varphi > 0$, it is straightforward to show that the equilibrium stock size declines as more and more ocean space is devoted to aquaculture. Fig. 1 depicts this relationship for an open-access fishery. As the value of φ increases, the effective carrying capacity will decrease. The fishing effort intercept of the population equilibrium curve stays fixed, but the curve rotates toward the origin, thereby reducing the steady state stock associated with any level of fishing effort. For a fixed level of fishing effort, say one with a management goal of achieving MSY (horizontal line in Fig. 1), yields must drop as the available stock declines.
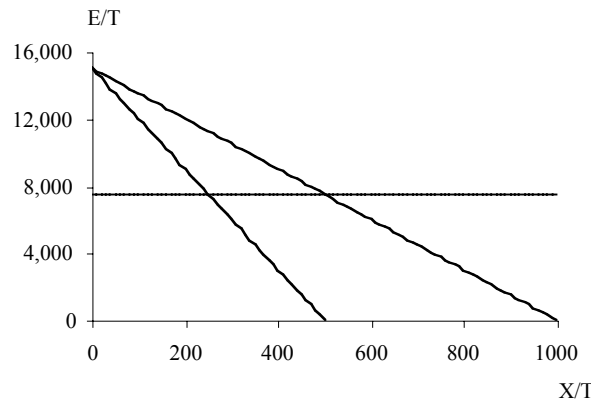

Fig. 1: Population equilibrium relationship for a fishery with contracting carrying capacity.

We now begin to consider some of the economic aspects. If we assume first that the fishery and aquaculture products are identical and undifferentiated in the market, then consumers should be indifferent with respect to the source of seafood. We model the total costs of fishing as an increasing linear function of fishing effort: TC = cE, where c is the unit cost of effort. In an open-access fishery, rents are dissipated, implying that it may be economically efficient for aquaculture to expand and to displace the fishery completely. This result is definitely true if aquaculture can generate producer surpluses and can produce at least as much fish as the open-access fishery was producing, because there will be no decrease in consumer surplus. Moreover, the economy conceivably might benefit more, even if somewhat less fish is produced by aquaculture, for two reasons: the open-access inefficiency would be reduced (or removed) and aquaculture producers might earn surpluses.

Another important consideration is what happens to the commercial fishing fleet. Ostensibly, there is no change in producer surpluses for fishermen, because resource rents are fully dissipated in open-access equilibrium. As the carrying capacity contracts, the sustainable revenue curve shifts down (Fig. 2). This shift forces the open-access fishing effort to decline, or, equivalently, it forces vessels to exit the fishery. Thus we might expect considerable opposition by commercial fishermen to the introduction of aquaculture, if it is expected to reduce the effective carrying capacity of the fishery.
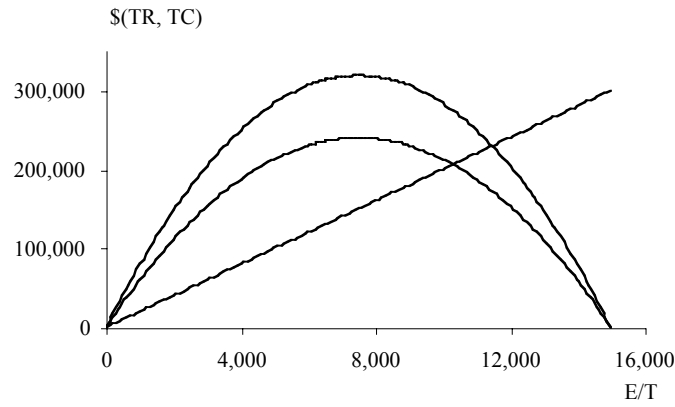
$(TR, TC)

Fig. 2: Decline in open-access fishing effort with contracting carrying capacity.

There will be opposition to aquaculture in an optimally managed fishery as well. Fig. 2 shows that both the optimal level of fishing effort and resource rents will decline as the carrying capacity contracts. To see this in another way, we can explore the relationship between the value of fishing quota, m, and changes in the carrying capacity. We assume the market price of fish, p, is a constant, and we discount the future at rate _. For an optimally managed fishery, the stock size can be solved as a function of the model parameters only (Clark 1990), including the important parameter K(S):

$$X^*(K(S)) = \frac{K(S)}{4}\left\{\left(\frac{c}{pqK(S)}+1-\frac{\delta}{r}\right)+\left[\left(\frac{c}{pqK(S)}+1-\frac{\delta}{r}\right)^2+\frac{8c\delta}{pqrK(S)}\right]^{\frac{1}{2}}\right\} \tag{4}$$

Define the value of fishing quota as follows:

$$m(K(S)) = p-\left(\frac{c}{qX(K(S))}\right) \tag{5}$$

Substituting the optimal stock size into equation (5) gives us a functional relationship between the price of quota and the effective carrying capacity, as shown in Fig. 3. Assuming that the fish stock is distributed uniformly over the fishing grounds, this relationship provides a way of measuring the opportunity cost of the expansion of aquaculture. If fishermen hold the property rights, then the curve represents a minimum compensation schedule for the purchase of rights to conduct aquaculture in the ocean.
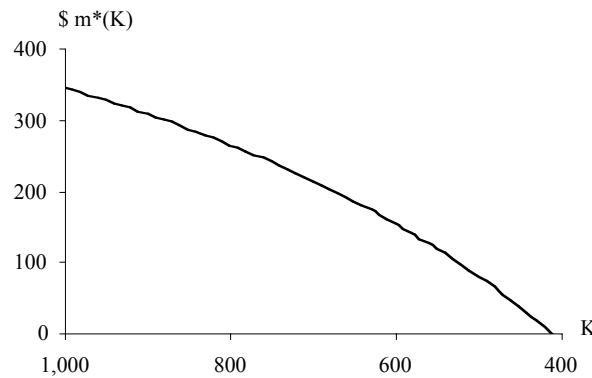

$ m*(K)

Fig. 3: Decline in the price of fish quota with contracting effective carrying capacity.

3. COMPETITION OVER SPACE AND IN THE MARKET

In order to explore the optimal allocation of space between a commercial fishery and aquaculture, we first need to characterize the economic dimensions of the aquaculture operation.[3] We specify a linear production function for aquaculture:

$$h_a = wS \tag{6}$$

where h_a is farmgate output and w is a positive coefficient. According to this model, a larger area S is needed if aquaculture is to increase its supply to the market. We assume that capital and labor are proportional to acreage. We model the costs of aquaculture as an increasing function of the total geographic area, S, allocated for aquaculture[4]:

$$\frac{\partial C_a}{\partial S} > 0 \tag{7}$$

Further, there is a cost of investment in aquaculture, I(z), in which z is an increment to the total acreage S:

$$\frac{\partial I}{\partial z} > 0 \tag{8}$$

We define total benefits as the sum of revenues from the commercial wild harvest of fish and the production of fish by aquaculture. Total benefits are a function of E, X and S:

$$B(E,X,S) = B_f(h_f) + B_a(h_a) \tag{9}$$

A hypothetical regional manager chooses the levels of fishing effort, E, and investment in aquaculture acreage, z, to maximize the net benefits of fish production from both the wild harvest fishery and aquaculture production:

$$\max \int_0^\infty \{B(E,X,S) - C_f(E) - C_a(S) - I(z)\}e^{-\delta t}dt \tag{10}$$

subject to

$$\dot{X} = F(X,S) - qEX \tag{11}$$

$$\dot{S} = z \tag{12}$$

The current-value Hamiltonian is:

$$H = B(E,X,S) - C_f(E) - C_a(S) - I(z) + \lambda[F(X,S) - qEX] + \beta z \tag{13}$$

The marginal conditions for an interior solution include:

$$\frac{\partial H}{\partial E} = \frac{\partial B}{\partial E} - \frac{\partial C_f}{\partial E} - \lambda qX = 0 \tag{14}$$

$$\frac{\partial H}{\partial z} = -\frac{\partial I}{\partial z} + \beta = 0 \tag{15}$$

$$\dot{\lambda} - \delta\lambda = -\frac{\partial H}{\partial X} = -\frac{\partial B}{\partial X} - \lambda\frac{\partial F}{\partial X} + \lambda qE \tag{16}$$

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[3] This framework is analogous to the multiobjective policy model for marine aquaculture developed by Sylvia *et al.* (1996), although we do not specify a set of "policy weights" on the two uses.

[4] It is also conceivable that the cost of fishing will be an increasing function of the space allocated to aquaculture, say, for example, because of gear conflicts or increased congestion. If this is true, then increases in S would tend to shift the total cost of fishing up at all levels of effort, resulting in a qualitative effect similar to the reduction of effective carrying capacity. In order to focus mainly on the effect of S on the reduction in carrying capacity, we do not model its effect on fishing costs. A more general model has been explored by Jin *et al.* (2002).

$$\dot{\beta} - \delta\beta = -\frac{\partial H}{\partial S} = -\frac{\partial B}{\partial S} + \frac{\partial C_a}{\partial S} - \lambda\frac{\partial F}{\partial S} \tag{17}$$

As an example, we assume that aquaculture will produce the same species as the commercial fishery and that the product is undifferentiated in the market. Take a linear demand function: $P = P_0 - \_(h_f + h_a)$, where P_0 is the choke price and _ is the slope. As a consequence, the benefit function (9) becomes:

$$B(E,X,S) \equiv \int_0^{h_f+h_a}(P_0 - \xi\eta)d\eta = P_0[h_f(E,X) + h_a(S)] - \frac{\xi}{2}[h_f(E,X) + h_a(S)]^2 \tag{18}$$

We specify the cost and investment functions as linear functions:

$$C_a = vS \tag{19}$$
$$I = bz \tag{20}$$

Equations (14) through (17) become

$$\lambda = P_0 - \xi(qXE + wS) - c/(qX) \tag{21}$$

$$\beta = b \tag{22}$$

$$\dot{\lambda} - \lambda[\delta - r + qE + 2rX/(K - \varphi S)] + qE[P_0 - \xi(qXE + wS)] = 0 \tag{23}$$

$$\dot{\beta} - \delta\beta + w[P_0 - \xi(qXE + wS)] - v - \lambda r\varphi X^2/(K - \varphi S)^2 = 0 \tag{24}$$

Assuming that a steady-state equilibrium is feasible, equations (21) through (24) can be used to solve for X as a function of E. S is a function of both E and X.

$$X = \frac{\varphi c(r - qE)^2}{rq(\delta b + v)} - \frac{c(\delta + r - qE)[wr - \varphi(r - qE)^2]}{rq(2qE - \delta - r)(\delta b + v)} \tag{25}$$

$$S = \frac{K}{\varphi} - \frac{rX}{\varphi(r - qE)} \tag{26}$$

The solution at steady-state can be determined as follows. First, for any E, calculate X using equation (25). Then calculate S using equation (26). Next, calculate λ at the steady state using equation (21), $d\lambda/dt = 0$. Finally, substitute E, X, S and λ into equation (24). The optimal level of effort, E*, is a positive solution to (24) when $d\beta/dt = 0$.

4.   MODEL SIMULATION

In order to examine the interactions between aquaculture and a commercial fishery, we consider a case in which aquaculture produces the same species as the commercial fishery. The growout of fluke in floating netpens (on the surface or submerged) has been proposed as a potential aquaculture product along the New England coast. One prototype fluke growout operation has been operating sporadically off the coast of Plum Island, New York in recent years (Link, p.c., 2002).[5] Fluke netpen operations can be stocked with juveniles produced at an onshore hatchery or by the wild harvest of juveniles in a nearshore pot fishery. We assume that the cost of juveniles from either source would be a part of the operational costs of the aquaculture operation. The product would be sold in the market for flatfish or, potentially, in the high end market for sushi. We focus on the former, as the market for the latter is not thought to be large (although it could be quite lucrative). Here, we abstract from the commercial harvest of other species, the important recreational fishery for fluke, and the effects of existing conservation and management measures, among other complications.

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[5] Another prototype, focusing on winter flounder (*Pleuronectes americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*), is under development by the University of New Hampshire off the coast of Isles of Shoals in the Gulf of Maine.

We borrow estimates of parameters from the literature. The US National Marine Fisheries Service has developed a surplus production model for fluke (SARC 2000). The model suggests an intrinsic growth rate, r, ranging from 0.49 to 1.08 year^{-1}.[6] We adopt the lower growth rate as a baseline for simulations. We use an estimate of the catchability, q, of yellowtail flounder (*Pleuronectes ferrugineus*) of 0.000011 days^{-1}, obtained from a study of the New England groundfish fishery (Edwards and Murawski 1993). We estimate a carrying capacity for fluke in Rhode island Sound of 35 million pounds (17,500 short tons [ST]), which is 15 percent of the current estimate of biomass capable of producing maximum sustainable yield (SARC 2000).[7]

We calculate an average price of $1.82 per pound ($3,640 ST^{-1}) for summer flounder from recent data on the national value of landings divided by national landings. Use of this price abstracts from regional and seasonal variations in price as well as premiums known to be paid in the market for different grades of fluke. We have been unable to find a published model of the demand for fluke, so we borrow a demand slope parameter, ξ, for yellowtail flounder of $0.017 ST^{-2} from the Edwards and Murawski (1993) study. We calculate a choke price, P_0, of $3,668 ST^{-1} for a linear demand curve using the slope parameter and the point represented by price and the 1999 Rhode Island commercial landings of fluke of 818 ST. The US Mid-Atlantic Fishery Management Council's fishery management plan for summer flounder, scup, and black sea bass identifies four size classes of trawlers that catch fluke, but most landings are made by the two intermediate size trawler classes (MAFMC 1998). We employ an average estimate of unit fishing costs, c, of $3,300 day^{-1} for these two classes, based upon unpublished data compiled by the NMFS Northeast Fisheries Science Center.

For the culturing of fluke, the following parameter estimates were obtained from a model developed at the WHOI Marine Policy Center (Kite-Powell *et al.* 2002b): annual yield, w, is 120 ST acre^{-1}; annual aquaculture production cost, v, is $470,000 acre^{-1}; and the cost of new investment, b, is $90,000 acre^{-1}. Investments in equipment are assumed to have a life of 15 years. Production costs include the costs of maintenance and the purchase of juveniles for growout.

If the net benefits from aquaculture exceed those from the commercial fishery, then a regional manager would want to allocate all of the available space to aquaculture and vice versa. When we run the model with our baseline parameter values, we find that it is optimal to allocate the entire region to aquaculture. Significant changes in any one or a combination of parameter values will produce the result that it is optimal for the entire region to be allocated for a wild harvest fishery. In general, we find that, given the current functional forms and parameter values, the model typically results in a corner solution favoring one of the two uses.

In order to examine more closely the nature of the tradeoffs between aquaculture and the fishery, we modify some of the baseline parameters so that the model produces an internal steady-state equilibrium. In effect, we constrain the model to produce the coexistence of both uses as the economically optimal outcome. We adjust carrying capacity, K, from 17,500 to 175,000 ST; aquaculture yield, w, from 120 to 200 ST acre^{-1}; aquaculture production cost, v, from $470,000 to $534,000 acre^{-1}; and we contract demand, while keeping the choke price fixed, by increasing ξ from $0.017 to $0.034 ST^{-2}. All of these parameter changes seem plausible, except possibly the increase in carrying capacity, which is larger by an order of magnitude.

Fig. 4 depicts production possibility surfaces in which aquaculture production measured along the ordinate is traded off against fishery landings measured along the abscissa. The points along any surface represent combinations of production possibilities for a fixed set of model parameters. Only one of these points, represented by the dot on each curve, represents the optimal combination of production. The figure shows how the production possibilities change when the parameter _, which affects the carrying capacity of the ecosystem for fluke, is varied by 20 percent. Here, an increase in _ from 100 to 120 ST acre^{-1}, representing a more significant negative impact of aquaculture on the carrying capacity, moves the optimal solution to the corner favoring commercial fishing; a decrease to 80 ST acre^{-1} moves the optimal solution to the corner favoring aquaculture. We attempt to explain this seemingly counterintuitive result below.

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[6] For comparison, in their study of the New England groundfish fishery, Edwards and Murawski (1993) employ an intrinsic growth rate of 0.23 for yellowtail flounder, a related species. The NMFS surplus production model is still under development, and it has not been utilized to manage the fishery to date.

[7] Fifteen percent is the average annual harvest share for Rhode Island during 1980-92 (MAFMC 1998).
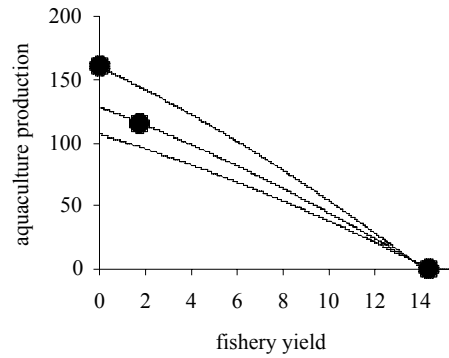
Fig. 4: Production possibility surfaces illustrating the tradeoffs between aquaculture and the wild harvest fishery as the interaction term _ is varied by ± 20 percent from a baseline interior solution (the black dot on the middle curve). Black dots represent points of optimality. Units are expressed in thousands of short tons (ST).

When the model is parameterized to yield an interior solution, we can examine the effects of small changes in each of the parameters on the optimal levels of the control, E, and state variables, S and X, in the model. The model exhibits varying degrees of sensitivity to changes in the range of parameters. In order to compare these sensitivities, we represent these changes as elasticities (ratios of percentage changes in the variable of interest to percentage changes in the parameter being varied) in the neighborhood of the "initial" values (Table 2, column 2). These elasticities are summarized in columns 4 through 6 of Table 2. Both the direction and size of these changes are of interest. Given the large number of parameters, we discuss only a few of the apparently counterintuitive results here.

All three variables are most sensitive to changes in the following three parameters: the unit cost of aquaculture, v, the marginal productivity of aquaculture, w, and the choke price, P_0. Interestingly, when the unit cost, v, of aquaculture increases, instead of making aquaculture less competitive with commercial fishing, the model selects a new optimum in which more acreage is allocated for aquaculture and less effort is devoted to commercial fishing.

Table 2: Results of sensitivity analyses showing the elasticities of model variables with respect to model parameters. Elasticities are evaluated in the neighborhood of the internal optimal solution for all of the initial values of the parameters. The parameters are varied one at a time while keeping all other parameters at their initial values.

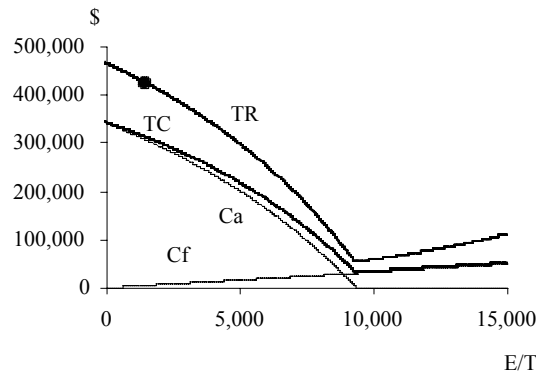|	Initial Values	Units	E	X	S
P_0	3640	$ ST^{-1}	307.61	7.37	-31.54
_	534	$ x10^3 AC^{-1}	-300.85	-7.99	37.02
w	0.200	STx10^3 AC^{-1}	267.61	7.40	-31.20
_	0.100	ST x10^3 AC^{-1}	25.35	0.60	-3.81
r	0.490	time^{-1}	13.96	0.30	-2.68
_	0.070	--	6.90	0.15	-0.73
b	90	$ x10^3 AC^{-1}	-3.49	-0.10	0.47
_	0.034	$ x10^{-3} ST^{-2}	-2.87	-0.07	0.35
c	3.300	$ x10^3 day^{-1}	-1.86	0.96	-1.83
q	0.000011	day^{-1}	1.08	-1.00	1.91
K	175	ST x10^3	-0.99	-0.02	3.15

Fig. 5: Total revenues and total costs as a function of commercial fishing effort for the baseline parameter values. Total costs are the sum of the costs of fishing effort C_f and the costs of aquaculture C_a. The maximum economic yield (in terms of both the fishery and aquaculture) is represented by the large dot on the total revenue curve. Note that total revenues depend upon production from both the fishery and aquaculture.

A geometric explanation for this result is as follows (Fig. 5). We begin with the total revenue (TR) curve. Starting near the ordinate, fishing effort is close to zero and the market is supplied predominantly with fish from aquaculture. As a consequence, most of the total revenues are generated by aquaculture. As we increase fishing effort, S declines according to equation (26). Under the current parameterization, however, aquaculture production is still quite large relative to fishery production, and so the shape of the TR curve is controlled mainly by the rate dS/dE and only in a minor way by the interaction between the harvest and growth of the wild fish stock. Thus, the TR curve declines with respect to fishing effort at an increasing rate. As fishing effort is increased even further, eventually aquaculture production ceases (at the inflection point) and fish are supplied entirely by the fishery. Note that, beyond this point, the shape of the TR curve is controlled by the shape of sustained yield from the fishery.[8]

A similar explanation holds for the shape of the C_a curve,[9] which also is a function of S(E). Thus the C_a curve exhibits the same general shape as the TR curve, but it declines at a slower rate. The total cost of fishing C_f increases linearly with fishing effort. As in the case of the TR curve, beginning from the ordinate, the total cost (TC) curve is made up almost completely of the total costs of aquaculture, and therefore is very close in shape to the C_a curve.

A separate but important effect occurs with changes in S that is not displayed in Fig. 5. Changes in the size of the fish stock X respond to changes in S. When aquaculture acreage declines, there is a reduced effect on the carrying capacity. As a consequence, the stock size can expand and vice versa.

Now, when the unit cost, ν, of aquaculture is increased, the C_a and TC curves shift up. The economic optimum shifts along TR to the left because such a move both reduces the total costs of fishing and increases (relatively speaking) the distance between the total costs of aquaculture and TR. As S increases with this shift of the optimum to the left, the "effective" fish stock X declines, therefore reinforcing the decline in fishing effort.

Qualitatively, the same explanation holds for the effects on fishing effort and aquaculture acreage of changes in the marginal productivity of aquaculture, w. In this case, however, the TR curve shifts up with increases in w, causing fishing effort to expand and aquaculture acreage to contract, and vice versa.

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[8] There is no guarantee that the shape of TR will be a symmetric logistic curve beyond the inflection point because of the nonlinearity of the TR curve (Anderson 1986).

[9] At the optimum, dS/dt = 0, implying that z =0. When we consider a move to a new optimum due to a change in parameter value, strictly speaking, we should adjust the total cost of aquaculture up (or down) by the cost of investment in new acreage: $bz \cong b\Delta S^*$. (When aquaculture acreage is decreased, we assume that the capital can be sold for a salvage value equal to its original price; i.e., there is no physical depreciation of capital.) Fig. 6 does not illustrate this effect, but it is not large enough to change the qualitative description of the response of the model variables to changes in _ and w.

5. CONCLUSIONS

A wide variety of potential interactions may arise between aquaculture and commercial fisheries. Depending upon the species and technologies involved, these interactions may be competitive or complementary. As an example of the latter, Hickman (1996) describes the merger of technologies from a wild harvest fishery and aquaculture to undertake spat collecting, growout, seabed seeding, and dredge harvesting in the New Zealand southern sea scallop fishery. More frequently, however, the two uses are competitive; and user conflicts could grow as aquaculture is increasingly looked to as a source of supply of seafood protein. We develop a framework for improving our understanding about these interactions. Our hope is that with this improved understanding we may be able to manage fishery resources more efficiently and to mitigate potential user conflicts.

We show first that the commercial fishery's equilibrium stock size declines as more ocean space is devoted to aquaculture. When the fishery is open-access, then it may be optimal for aquaculture to displace the fishery—even where aquaculture is producing a different species. This result depends upon the size of consumer surpluses for the products of the two uses and the fact that rents are dissipated in the open-access fishery. Under the right conditions, the entry of aquaculture also could force wild harvest fishermen to exit the fishery, implying that there may be considerable political opposition to aquaculture in an established fishery—even if it is managed for maximum economic yield. We consider the nature of the tradeoff between a rights-based fishery with rights to quota and aquaculture with rights to geographic space. Where the fishery has pre-eminent rights, the relationship between the value of quota and the effective carrying capacity, which may vary with the scale of aquaculture development, defines a minimum compensation schedule for quota holders—assuming that the fish stock is uniformly distributed over the fishery.

In this paper, we develop a framework to analyze the tradeoffs between a wild harvest fishery and aquaculture where they occur in the same region (defined by the fishery) and sell into the same market. In the framework, aquaculture affects the fishery's carrying capacity and supplies a portion of the market. The framework can be used to identify the economically optimal scale of both aquaculture and a commercial fishery. Our results suggest that when aquaculture exerts a significant negative impact on the fishery, the economic optimum often is associated with a corner solution of the model (*i.e.*, the region should be allocated exclusively for either aquaculture or commercial fishing), and the coexistence of both uses is suboptimal. Using baseline parameters for a hypothetical case involving fluke in Rhode Island Sound, we were unable to find a superior equilibrium solution involving the coexistence of both uses. In general, if the net benefits from aquaculture exceed those from commercial fishing, then it is economically optimal to replace the fishery with aquaculture (and vice versa). We note that economically optimal adjustments along the path to equilibrium or, what is even more likely, political accommodations could well lead to a situation where both uses coexist. Further, we have abstracted from the real world where other uses, including nonmarket uses such as recreational fishing and ecosystem conservation, should enter into allocation decisions.

With modified parameter values, we examine internal steady-state solutions to consider what happens when both uses are "constrained" to coexist. The framework shows that the optimal values of the control and state variables are most sensitive to the choke price, and to both the unit cost and marginal productivity of aquaculture. We find, counterintuitively, that the optimal scale of aquaculture expands (and optimal commercial fishing effort contracts) when the unit cost of aquaculture increases or when the marginal productivity of aquaculture decreases. This result is due to the influence exerted by aquaculture production on the shape of total revenues and aquaculture costs. An important question for future research concerns the generalizability of this result to real world examples of aquaculture-fishery interactions.

6. ACKNOWLEDGEMENTS

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